QCD phenomenology from DSEs

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in collaboration with:

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Content

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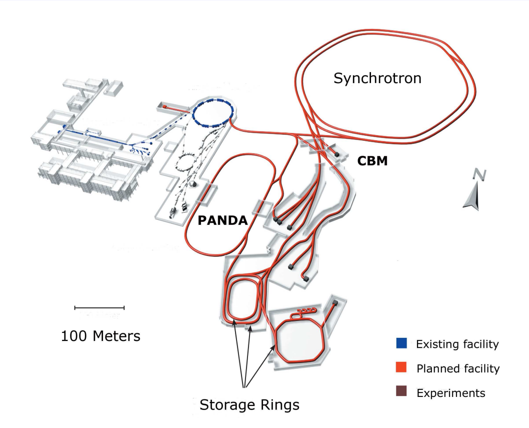
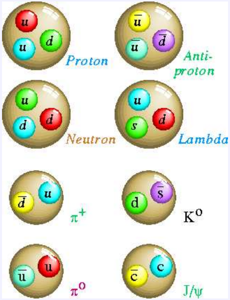
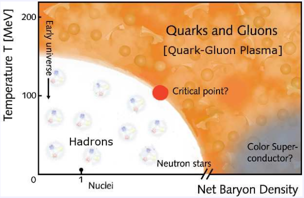
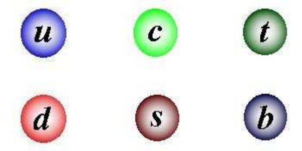
FAIR: CBM and PANDA







Dynamical mass generation

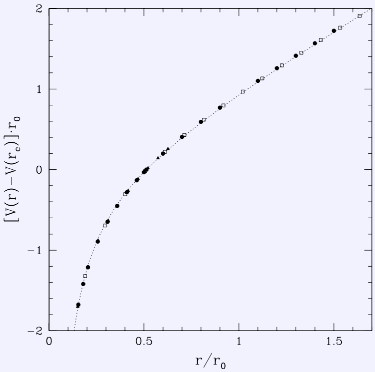


Quark mass generated by weak and strong interaction
(QCD: explicit vs. dynamical breaking of chiral symmetry)

	u	d	s	c	b	t
M_{weak} [MeV]	3	5	100	1300	4000	175000
M_{strong} [MeV]	400	400	400	400	400	400
M_{tot} [MeV]	400	400	500	1700	4400	175000

M_{strong}: **Nonperturbative effect!**

Confinement



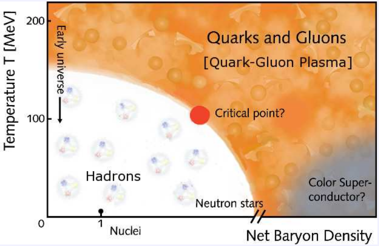
S. Necco and R. Sommer, Nucl. Phys. B **622** (2002) 328

- Linear rising potential: $V(r) \sim r$
- Quark-Antiquark system cannot be split: Quark-Confinement
- Screening of gluons $\rightarrow$ Glueballs

What are the driving mechanisms?
Consequences for hadronic spectra ?

CBM: QCD phase transitions

- Existence and location of critical end point
- Propagation of quarks and gluons in plasma phase



- Chiral limit ($M_{weak} \to 0$): order parameter chiral condensate

$$\langle \bar{\psi}\psi \rangle = Z_2 N_c Tr_D \int \frac{d^4p}{(2\pi)^4} S(p)$$

- Static quarks ($M_{weak} \to \infty$): order parameter Polyakov-loop

$$\Phi \sim e^{-F_q/T} \quad \leftrightarrow \quad \int_\varphi \langle \bar{\psi}\psi \rangle_\varphi$$

CBM/FAIR-Experiment

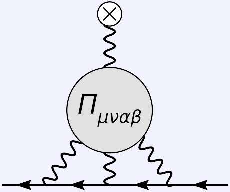
Experiment: $11\,659\,2080(63) \times 10^{-11}$

G. W. Benett *et al.* (Muon g-2 Collaboration), PRD **73**, 072003 (2006)

Theory: $11\,659\,1790(65) \times 10^{-11}$

F. Jegerlehner and A. Nyffeler, Phys. Rept. **477**, 1 (2009)

Problem: Hadronic 'LBL-contribution' with $116(39) \times 10^{-11}$:



- Cannot be determined from experimental input
- Multi-Scale problem!
- $\rightarrow$ NJL-model, VMD,... (Prades, Nyffeler, et al.)

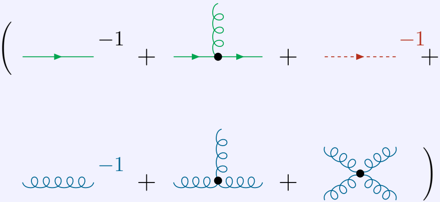
Goal: 'Ab initio' calculation of LBL contribution

QCD in covariant gauge

quarks, gluons and ghosts:

$$\mathcal{Z}_{QCD} = \int \mathcal{D}[\Psi, A, c] \; \exp\left\{ - \int d^4x \left(\overline{\Psi}\,(i\not{D} - m)\,\Psi - \frac{1}{4}\left(F^a_{\mu\nu}\right)^2 + \frac{(\partial A)^2}{2\xi} + \bar{c}(-\partial D)c \right) \right\}$$

$$S_{QCD} = \int d^4x$$



Green's functions

QCD Green's functions

- are connected to confinement:
  - Gribov-Zwanziger and Kugo-Ojima scenarios
  - Running Coupling
  - Positivity
  - Polyakov Loop
- encode DχSB
- are ingredients for hadron phenomenology
  - Bound state equations:
    Bethe–Salpeter equation / Faddeev equation
  - Form factors, decays etc.

The Goal:

Gauge invariant information from gauge fixed functional approach

The Tool:

Dyson-Schwinger and Bethe-Salpeter-equations (DSE/BSE)

Lattice QCD vs. DSE/FRG: Complementary!

- Lattice simulations
  - Ab initio
  - Gauge invariant
- Functional approaches:
  Dyson-Schwinger equations (DSE)
  Functional renormalisation group (FRG)
  - Analytic solutions at small momenta
  - Space-Time-Continuum
  - Chiral symmetry: light quarks and mesons
  - Multi-scale problems feasible: e.g. $(g\text{-}2)_\mu$
  - Chemical potential: no sign problem

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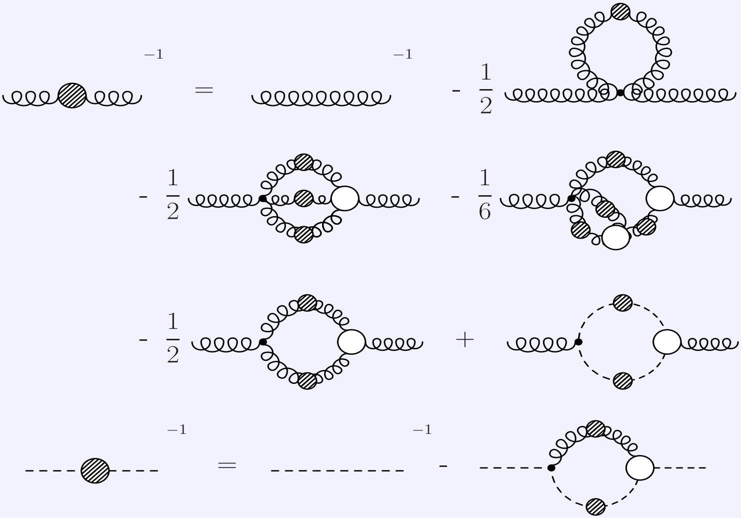
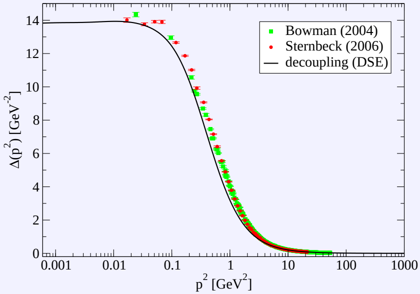
Dyson-Schwinger equations (DSEs)



Gluon propagator ($T = 0$)



C.F., Maas and Pawlowski, Annals Phys. **324** (2009) 2408.

Aguilar, Binosi, Papavassiliou, PRD **78**, 025010 (2008).

Cornwall, PRD **26** (1982) 1453.

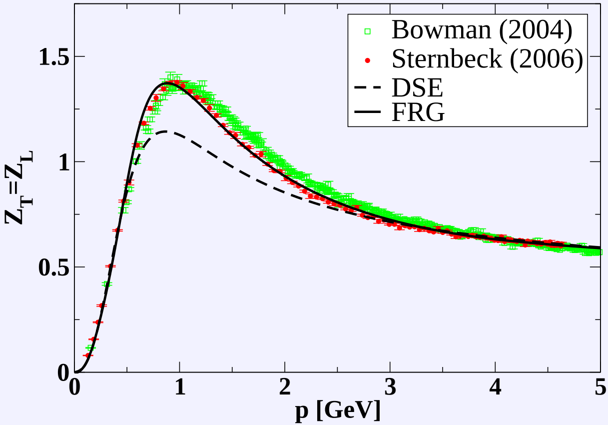
$$\Delta(p^2) = \frac{Z(p^2)}{p^2}$$

- Gluon 'mass' generation in agreement with lattice results

  Cucchieri, Mendes, PoS **LAT2007** (2007) 297.

- Analytic structure of glue incl. positivity violations
  $\rightarrow$ **talk of Stefan Strauss**

Gluon dressing function ($T = 0$)



- DSE vs FRG: Effect of four-gluon-interaction
- Physics is in mid-momentum region !

C.F., A. Maas and J. M. Pawlowski, Annals Phys. **324** (2009) 2408-2437.

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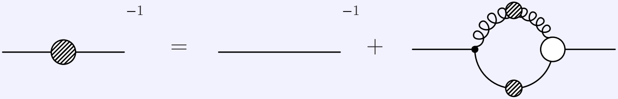
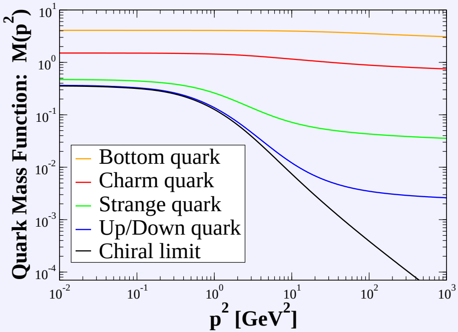
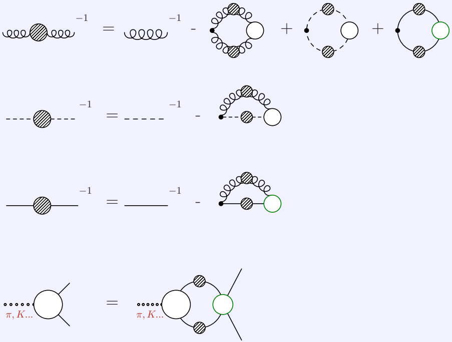
Explicit vs. dynamical chiral symmetry breaking





- $M(p^2)$: momentum dependent!
- Dynamical masses $M_{strong}(0) \approx 350 MeV$
- Flavour dependence because of M_{weak}

From gluons and quarks to mesons



- Central quantity:
  quark-gluon vertex
  Alkofer, C.F., Llanes-Estrada, Schwenzer,
  Annals Phys.324:106-172,2009.

- Meson structure beyond rainbow-ladder
  C.F. and Williams, PRD **78**, 074006 (2008).
  C.F. and Williams, PRL **103** (2009) 122001.

- Baryon structure
  $\rightarrow$ **talk of Gernot Eichmann**

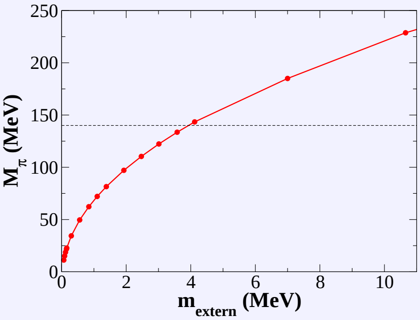
- $U_A(1)$-problem

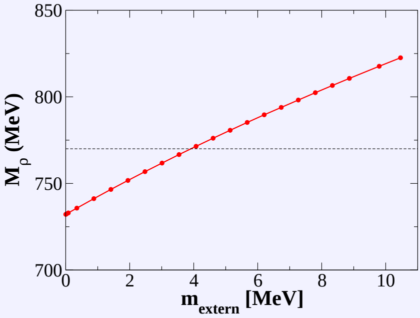
  Alkofer, C.F. and Williams, Eur. Phys. J. A **38**, 53 (2008)

- $\pi\gamma\gamma$ and g-2

  Goecke, C.F., Williams, PRD 83 (2011) 094006.

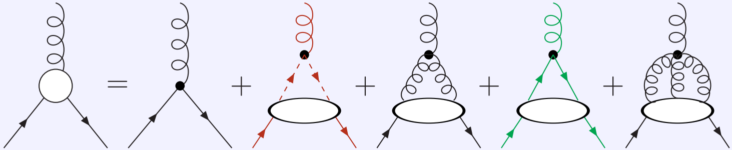
Pions and Rho-Mesons



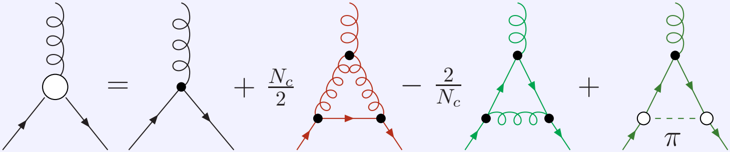


- $m_{u,d} \to 0$: $\quad m_\pi^2 f_\pi^2 = (m_u + m_d)\langle\bar{\psi}\psi\rangle$
  Pion is masseless Goldstone-boson with massive constituents
- Simple model: 'rainbow-ladder approximation'
  only vector coupling between quark and gluon included

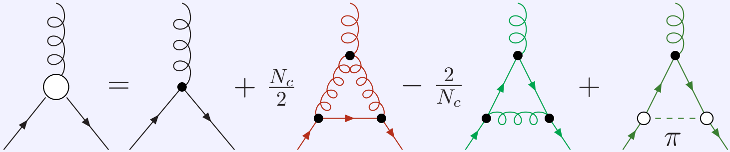
P. Maris and C. D. Roberts, Phys. Rev. C **56** (1997) 3369



- Truncation via skeleton expansion leads to (all propagators and vertices dressed!):



Quark-gluon vertex II



- Abelian diagram extensively explored

  Roberts, Tandy, Thomas, Watson *et al.*

- Gluon self-interaction leading in large N_c
- Gluon self-interaction also leading at $N_c = 3$

  Alkofer, C.F., Llanes-Estrada, Schwenzer, Annals Phys.324:106-172,2009.

  C.F, R. Williams, PRL **103** (2009) 122001

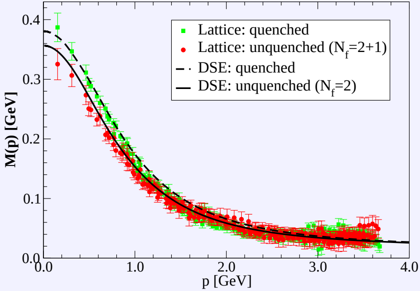
- Pion backreaction $\rightarrow$ pion cloud effects

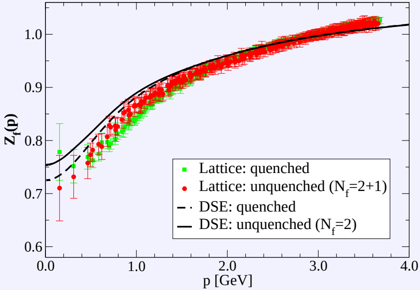
  C.F, D. Nickel and J. Wambach, PRD **76** (2007) 094009

  C.F., D. Nickel and R. Williams, EPJC **60**, 1434 (2008)

  C.F. and R. Williams, PRD **78**, 074006 (2008).

Pion cloud effects in the quark propagator





CF, D. Nickel and R. Williams, EPJC **60**, 1434 (2008)

- Unquenching effects of similar size as lattice

  P. O. Bowman, et al. Phys. Rev. D **71** (2005) 054507

Pion cloud effects in light mesons

	RL	3g	3g+π	Experiment
M_π	138	138	138	138
f_π	94	111	105	93
M_ρ	758	881	805	776
f_ρ	154	176	168	162
M_σ	645	884	820	450
M_{a_1}	926	1055	1040	1230
M_{b_1}	912	972	940	1229

- Attractive effects of 'pion cloud'
- Corrections from decay channels missing

CF and R. Williams, PRL **103** 122001 (2009).

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Hadronic contributions to g-2 I

Experiment: $11\,659\,2080(63) \times 10^{-11}$

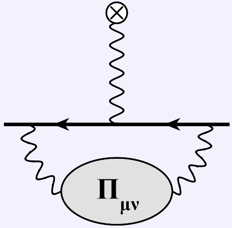
G. W. Benett *et al.* (Muon g-2 Collaboration), PRD **73**, 072003 (2006)

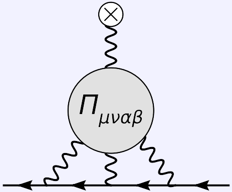
Theory: $11\,659\,1790(65) \times 10^{-11}$

F. Jegerlehner and A. Nyffeler, Phys. Rept. **477**, 1 (2009)

Hadronic contributions:

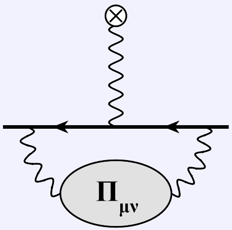
vacuum polarization and light-by-light scattering

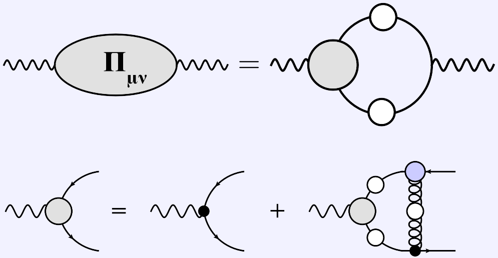




Goal: 'Ab initio' calculation of LBL contribution

Results: hadronic vacuum polarisation



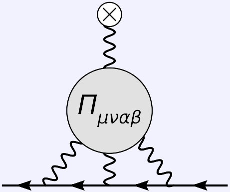


- Building blocks: quark propagator and quark-photon vertex
- $\rightarrow$ our value ($N_f = 5$): $(a_\mu^{HVP})_{DSE} = 6760 \times 10^{-11}$
  $(a_\mu^{HVP})_{Exp.} = 6949.1(37.2)(21.0) \times 10^{-11}$

T. Goecke, C.F., R. Williams, PLB in press, arXiv:1107.2588

K. Hagiwara, R. Liao, A. D. Martin, D. Nomura, T. Teubner, J. Phys. G **G38** (2011) 085003

Results: anomalous magnetic moment



Group	Approach	π^0, η, η'	quark-loop
BPP	ENJL	85(13)	21(3)
KN	LMD+V	83(12)	–
MV	LMD+V	114(10)	short distance
	DSE	84(13)	107(48)

J. Bijnens, E. Pallante and J. Prades Phys. Rev. Lett. **75**, 1447 (1995)
M. Knecht and A. Nyffeler, Phys. Rev. D **65** 073034 (2002)
K. Melnikov and A. Vainshtein, Phys. Rev. D **70** 113006 (2004)
T. Goecke, C.F., R. Williams, PRD 83 (2011) 094006.

C.F., T. Goecke and R. Williams, in preparation

Total result:

$$\text{Experiment: } 11\,659\,2080(63) \times 10^{-11}$$

G. W. Benett *et al.* (Muon g-2 Collaboration), PRD **73**, 072003 (2006)

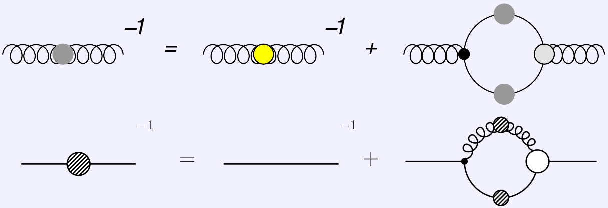
$$\text{Our value: } 11\,659\,1865(97) \times 10^{-11}$$

C.F., T. Goecke and R. Williams, in preparation

$\rightarrow$ **talk of Tobias Goecke**

Content

The ordinary chiral condensate



- Order parameter for chiral symmetry breaking: condensate

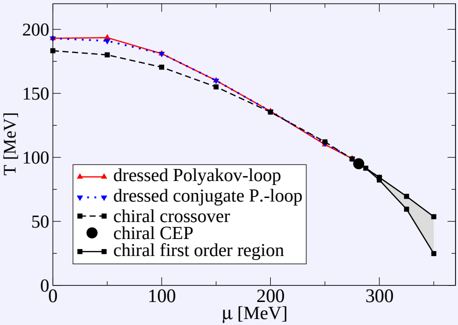
$$\langle\bar{\psi}\psi\rangle = Z_2 N_c T \sum_{n_p} \int \frac{d^3p}{(2\pi)^3}\, Tr_D\, S(\vec{p}, \omega_p)$$

- Order parameter for deconfinement: dressed Polyakov loop

$$\Sigma_1 \quad = \quad - \int_0^{2\pi} \frac{d\varphi}{2\pi}\, e^{-i\varphi} \langle\bar{\psi}\psi\rangle_\varphi$$

C.F., PRL **103** (2009) 052003
Synatschke, Wipf and Wozar, PRD **75**, 114003 (2007).
Bilgici, Bruckmann, Gattringer and Hagen, PRD **77** 094007 (2008).

$N_f = 2$: QCD phase diagram



C.F., J. Luecker, J. A. Mueller, PLB 702 (2011) 438-441.

→ **talk of Jan Luecker**

- CEP at $(T, \mu) \simeq (95, 280)$ MeV
- in agreement with expectations from lattice

  de Forcrand, Philipsen, JHEP **0811** (2008) 012; Nucl. Phys. **B642** (2002) 290-306.

  G. Endrodi, Z. Fodor, S. D. Katz, K. K. Szabo, JHEP **1104** (2011) 001.
- qualitative agreement with PQM model

  Herbst, Pawlowski, Schaefer, PLB **696** (2011)
- imaginary chemical potential (FRG):

  Braun, Haas, Marhauser, Pawlowski, PRL 106 (2011)

Thank you for your attention!

Helmholtz Young Investigator Group "Nonperturbative Phenomena in QCD"

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